



Modern Wireless Communications

SIMON HAYKIN • MICHAEL MOHER



Contents

Preface **xiii**

Chapter 1 **Introduction** **1**

- 1.1 Background 1
- 1.2 Communication Systems 3
- 1.3 The Physical Layer 3
- 1.4 The Data-Link Layer 5
 - 1.4.1 FDMA 5
 - 1.4.2 TDMA 6
 - 1.4.3 CDMA 7
 - 1.4.4 SDMA 8
- 1.5 Overview of the Book 8
- Notes and References 10

Chapter 2 **Propagation and Noise** **11**

- 2.1 Introduction 11
- 2.2 Free-Space Propagation 13
 - 2.2.1 Isotropic Radiation 13
 - 2.2.2 Directional Radiation 15
 - 2.2.3 The Friis Equation 18
 - 2.2.4 Polarization 19
- 2.3 Terrestrial Propagation: Physical Models 19
 - 2.3.1 Reflection and the Plane-Earth Model 20
 - 2.3.2 Diffraction 24
 - 2.3.3 Diffraction Losses 28
- 2.4 Terrestrial Propagation: Statistical Models 30
 - 2.4.1 Median Path Loss 30
 - 2.4.2 Local Propagation Loss 32
- 2.5 Indoor Propagation 33
- 2.6 Local Propagation Effects with Mobile Radio 36
 - 2.6.1 Rayleigh Fading 36
 - 2.6.2 Rician Fading 40

vi	Contents	
	2.6.3	Doppler 42
	2.6.4	Fast Fading 44
2.7	Channel Classification	48
	2.7.1	Time-Selective Channels 50
	2.7.2	Frequency-Selective Channels 52
	2.7.3	General Channels 52
	2.7.4	WSSUS Channels 54
	2.7.5	Coherence Time 57
	2.7.6	Power-Delay Profile 58
	2.7.7	Coherence Bandwidth 60
	2.7.8	Stationary and Nonstationary Channels 61
	2.7.9	Summary of Channel Classification 62
2.8	Noise and Interference	63
	2.8.1	Thermal Noise 63
	2.8.2	Equivalent Noise Temperature and Noise Figure 66
	2.8.3	Noise in Cascaded Systems 68
	2.8.4	Man-Made Noise 70
	2.8.5	Multiple-Access Interference 71
2.9	Link Calculations	75
	2.9.1	Free-Space Link Budget 75
	2.9.2	Terrestrial Link Budget 80
2.10	Theme Example 1: Okumura–Hata Empirical Model	82
2.11	Theme Example 2: Wireless Local Area Networks	85
	2.11.1	Propagation Model 85
	2.11.2	Receiver Sensitivity 85
	2.11.3	Range 86
	2.11.4	Power-Delay Profile 86
	2.11.5	Modulation 88
2.12	Theme Example 3: Impulse Radio and Ultra-Wideband	89
2.13	Summary and Discussion	94
	Notes and References	95
	Additional Problems	96

Chapter 3 Modulation and Frequency-Division Multiple Access 103

3.1	Introduction	103
3.2	Modulation	105
	3.2.1	Linear and Nonlinear Modulation Processes 106
	3.2.2	Analog and Digital Modulation Techniques 107
	3.2.3	Amplitude and Angle Modulation Processes 107
3.3	Linear Modulation Techniques	108
	3.3.1	Amplitude Modulation 108
	3.3.2	Binary Phase-Shift Keying 110
	3.3.3	Quadriphase-Shift Keying 112

3.3.4	Offset Quadrature-Shift Keying	114
3.3.5	$\pi/4$ -Shifted Quadrature-Shift Keying	116
3.4	Pulse Shaping	116
3.4.1	Root Raised-Cosine Pulse Shaping	119
3.5	Complex Representation of Linear Modulated Signals and Band-Pass Systems	122
3.5.1	Complex Representation of Linear Band-Pass Systems	124
3.6	Signal-Space Representation of Digitally Modulated Signals	126
3.7	Nonlinear Modulation Techniques	130
3.7.1	Frequency Modulation	130
3.7.2	Binary Frequency-Shift Keying	132
3.7.3	Continuous-Phase Modulation: Minimum Shift Keying	133
3.7.4	Power Spectra of MSK Signal	137
3.7.5	Gaussian-Filtered MSK	139
3.8	Frequency-Division Multiple Access	142
3.9	Two Practical Issues of Concern	144
3.9.1	Adjacent Channel Interference	144
3.9.2	Power Amplifier Nonlinearity	146
3.10	Comparison of Modulation Strategies for Wireless Communications	148
3.10.1	Linear Channels	148
3.10.2	Nonlinear Channels	150
3.11	Channel Estimation and Tracking	151
3.11.1	Differential Detection	152
3.11.2	Pilot Symbol Transmission	154
3.12	Receiver Performance: Bit Error Rate	158
3.12.1	Channel Noise	158
3.13	Theme Example 1: Orthogonal Frequency-Division Multiplexing	162
3.13.1	Cyclic Prefix	167
3.14	Theme Example 2: Cordless Telecommunications	168
3.15	Summary and Discussion	170
	Notes and References	171
	Additional Problems	173

Chapter 4 Coding and Time-Division Multiple Access 179

4.1	Introduction	179
4.2	Sampling	182
4.3	Why Follow Sampling with Coding?	184
4.4	Shannon's Information Theory	185
4.4.1	Source-Coding Theorem	185
4.4.2	Channel-Coding Theorem	186
4.4.3	Information Capacity Theorem	187
4.4.4	Rate Distortion Theory	188
4.5	Speech Coding	189
4.5.1	Linear Prediction	189

4.5.2	Multipulse Excited LPC	190
4.5.3	Code-Excited LPC	192
4.6	Error-Control Coding	193
4.6.1	Cyclic Redundancy Check Codes	194
4.7	Convolutional Codes	195
4.7.1	Trellis and State Diagrams of Convolutional Codes	198
4.7.2	Free Distance of a Convolutional Code	200
4.8	Maximum-Likelihood Decoding of Convolutional Codes	201
4.9	The Viterbi Algorithm	203
4.9.1	Modifications of the Viterbi Algorithm	205
4.10	Interleaving	207
4.10.1	Block Interleaving	208
4.10.2	Convolutional Interleaving	210
4.10.3	Random Interleaving	212
4.11	Noise Performance of Convolutional Codes	212
4.12	Turbo Codes	215
4.12.1	Turbo Encoding	215
4.12.2	Turbo Decoding	216
4.12.3	Noise Performance	218
4.12.4	Maximum a Posteriori Probability Decoding	219
4.13	Comparison of Channel-Coding Strategies for Wireless Communications	222
4.13.1	Encoding	223
4.13.2	Decoding	224
4.13.3	AWGN Channel	225
4.13.4	Fading Wireless Channels	225
4.13.5	Latency	225
4.13.6	Joint Equalization and Decoding	226
4.14	RF Modulation Revisited	226
4.15	Baseband Processing for Channel Estimation and Equalization	227
4.15.1	Channel Estimation	229
4.15.2	Viterbi Equalization	231
4.16	Time-Division Multiple Access	233
4.16.1	Advantages of TDMA over FDMA	234
4.16.2	TDMA Overlaid on FDMA	235
4.17	Theme Example 1: GSM	236
4.18	Theme Example 2: Joint Equalization and Decoding	239
4.18.1	Computer Experiment	241
4.19	Theme Example 3: Random-Access Techniques	243
4.19.1	Pure Aloha	243
4.19.2	Slotted Aloha	245
4.19.3	Carrier-Sense Multiple Access	245
4.19.4	Other Considerations with Random-Access Protocols	248

4.20	Summary and Discussion	249
	Notes and References	251
	Additional Problems	252
Chapter 5 Spread Spectrum and Code-Division Multiple Access 258		
5.1	Introduction	258
5.2	Direct-Sequence Modulation	260
	5.2.1 The Spreading Equation	260
	5.2.2 Matched-Filter Receiver	262
	5.2.3 Performance with Interference	263
5.3	Spreading Codes	265
	5.3.1 Walsh–Hadamard Sequences	267
	5.3.2 Orthogonal Variable Spreading Factors	269
	5.3.3 Maximal-Length Sequences	270
	5.3.4 Scramblers	274
	5.3.5 Gold Codes	274
	5.3.6 Random Sequences	276
5.4	The Advantages of CDMA for Wireless	279
	5.4.1 Multiple-Access Interference	279
	5.4.2 Multipath Channels	283
	5.4.3 RAKE Receiver	284
	5.4.4 Fading Channels	288
	5.4.5 Summary of the Benefits of DS-SS	289
5.5	Code Synchronization	290
5.6	Channel Estimation	292
5.7	Power Control: The Near–Far Problem	294
5.8	FEC Coding and CDMA	297
5.9	Multiuser Detection	299
5.10	CDMA in a Cellular Environment	301
5.11	Frequency-Hopped Spread Spectrum	306
	5.11.1 Complex Baseband Representation of FH-SS	307
	5.11.2 Slow-Frequency Hopping	308
	5.11.3 Fast-Frequency Hopping	310
	5.11.4 Processing Gain	310
5.12	Theme Example 1: IS-95	311
	5.12.1 Channel Protocol	311
	5.12.2 Pilot Channel	313
	5.12.3 Downlink CDMA Channels	314
	5.12.4 Power Control	316
	5.12.5 Cellular Considerations	317
	5.12.6 Uplink	318
5.13	Theme Example 2: GPSS	319
5.14	Theme Example 3: Bluetooth	321

5.15	Theme Example 4: WCDMA	323
5.15.1	Bandwidth and Chip Rate	324
5.15.2	Data Rates and Spreading Factor	324
5.15.3	Modulation and Synchronization	324
5.15.4	Forward Error-Correction Codes	324
5.15.5	Channel Types	325
5.15.6	Uplink	325
5.15.7	Downlink	326
5.15.8	Multicode Transmission	327
5.15.9	Cellular Considerations	327
5.16	Theme Example 5: Wi-Fi	328
5.17	Summary and Discussion	331
	Notes and References	332
	Additional Problems	333
Chapter 6 Diversity, Capacity, and Space-Division Multiple Access		339
6.1	Introduction	339
6.2	“Space Diversity on Receive” Techniques	341
6.2.1	Selection Combining	341
6.2.2	Maximal-Ratio Combining	346
6.2.3	Equal-Gain Combining	353
6.2.4	Square-Law Combining	353
6.3	Multiple-Input, Multiple-Output Antenna Systems	357
6.3.1	Coantenna Interference	358
6.3.2	Basic Baseband Channel Model	360
6.4	MIMO Capacity for Channel Known at the Receiver	363
6.4.1	Ergodic Capacity	363
6.4.2	Two Other Special Cases of the Log-Det Formula: Capacities of Receive and Transmit Diversity Links	366
6.4.3	Outage Capacity	367
6.4.4	Channel Known at the Transmitter	371
6.5	Singular-Value Decomposition of the Channel Matrix	371
6.5.1	Eigendecomposition of the Log-det Capacity Formula	374
6.6	Space-Time Codes for MIMO Wireless Communications	376
6.6.1	Preliminaries	378
6.6.2	Alamouti Code	379
6.6.3	Performance Comparison of Diversity-on-Receive and Diversity-on-Transmit Schemes	387
6.6.4	Generalized Complex Orthogonal Space-Time Block Codes	389
6.6.5	Performance Comparisons of Different Space-Time Block Codes Using a Single Receiver	392
6.7	Differential Space-Time Block Codes	395
6.7.1	Differential Space-Time Block Coding	395

6.7.2	Transmitter and Receiver Structures	401
6.7.3	Noise Performance	402
6.8	Space-Division Multiple Access and Smart Antennas	404
6.8.1	Antenna Arrays	406
6.8.2	Multipath with Directional Antennas	412
6.9	Theme Example 1: BLAST Architectures	415
6.9.1	Diagonal-BLAST Architecture	416
6.9.2	Vertical-BLAST Architecture	417
6.9.3	Turbo-BLAST Architecture	419
6.9.4	Experimental Performance Evaluation of Turbo-BLAST versus V-BLAST	422
6.10	Theme Example 2: Diversity, Space-Time Block Codes, and V-BLAST	426
6.10.1	Diversity-on-Receive versus Diversity-on-Transmit	426
6.10.2	Space-Time Block Codes versus V-BLAST	427
6.10.3	Diversity Order and Multiplexing Gain	429
6.11	Theme Example 3: Keyhole Channels	432
6.12	Summary and Discussion	436
	Notes and References	439
	Additional Problems	441

Chapter 7 Wireless Architectures 450

7.1	Introduction	450
7.2	Comparison of Multiple-Access Strategies	450
7.3	OSI Reference Model	454
7.4	The OSI Model and Wireless Communications	457
7.5	MAC Sublayer Signaling and Protocols	458
7.6	Power Control	461
7.6.1	Open Loop	462
7.6.2	Closed Loop	463
7.6.3	Outer-Loop Power Control	464
7.6.4	Other Considerations	464
7.7	Handover	465
7.7.1	Handover Algorithms	465
7.7.2	Multiple-Access Considerations	466
7.8	Network Layer	467
7.8.1	Cellular Networks	467
7.8.2	Indoor LANs	469
7.9	Theme Example 1: Wireless Telephone Network Standards	470
7.10	Theme Example 2: Wireless Data Network Standards	472
7.11	Theme Example 3: IEEE 802.11 MAC	473
7.12	Summary and Discussion	475
	Notes and References	476
	Problems	476

Appendix A	Fourier Theory	479
Appendix B	Bessel Functions	493
Appendix C	Random Variables and Random Processes	496
Appendix D	Matched Filters	509
Appendix E	Error Function	516
Appendix F	MAP Algorithm	520
Appendix G	Capacity of MIMO Links	522
Appendix H	Eigendecomposition	533
Appendix I	Adaptive Array Antennas	536
Bibliography		544
Index		551